LOSS AND RECOVERY OF THE FIRST DMSP BLOCK 5D SPACECRAFT, SEPTEMBER 1976 TO MAY 1977: A CASE STUDY

by

Timothy C. Hanley

Office of History
Headquarters
6592 Air Base Group
Los Angeles Air Force Station
United States Air Force
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Approved by:

Thomas W. Morgan
THOMAS W. MORGAN
LtGeneral, USAF
Commander

FOREWORD

This study was prepared at the direction of LtGeneral Thomas W. Morgan, Commander of the Space and Missile Systems Organization, and was written by Timothy C. Hanley, a member of the staff of the Office of History, 6592nd Air Base Group. The study describes the recovery of the first Defense Meteorological Satellite Program Block 5D satellite, which was launched on 11 September 1976 and began to tumble immediately after attaining orbit. The satellite was returned to operational condition by using magnetic coils aboard the spacecraft to slow down the tumbling and by using specially developed computer programs to regulate the operation of the coils. This was the first time that these techniques had been used to recover a spacecraft, and the recovery constituted a significant advance in space technology for that reason.

Thomas S. Snyder

THOMAS S. SNYDER, Ph.D.
Chief, Office of History
6592nd Air Base Group

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CHRONOLOGY

29 Jun 76	The spacecraft was shipped to Vandenberg AFB.
2 Sep 76	Testing of the spacecraft at Vandenberg was completed.
11 Sep 76	The spacecraft was launched. Following its injection into orbit, it spun up, lost power, and lost communication with earth.
20 Sep 76	A failure review team was convened.
5 Oct 76	Contact between the spacecraft and the ground was reestablished.
6 Oct-31 Oct 76	Efforts to stabilize power, control spin axis drift, and evaluate system health were successfully completed.
1 Nov 76	A recovery team was organized.
30 Nov-3 Dec 76	Phase I of the recovery was executed; the spin rate of the spacecraft was reduced from 3.2 rpms to 2.8 rpms.
16 Jan-30 Jan 77	Phase II of the recovery was executed; the spin rate of the spacecraft was reduced from 2.8 rpms to .5 rpms.
28 Feb 77	An attempt was made to execute Phase III of the recovery; the attempt was suspended when an abnormality was detected in the spacecraft's roll gyro.
24 Mar 77	A second attempt was made to execute Phase III of the recovery; the spin rate of the spacecraft was successfully reduced from .5 rpms to .03 rpms, and the spacecraft's attitude control system began normal operation.

28 Mar 77	A software patch was uploaded into one of the spacecraft's computers, allowing its attitude control system to function without the roll gyro.
1 Apr 77	The spacecraft was declared operational.
28 Apr 77	General William J. Evans, Commander of AFSC, visited SAMSO and presented medals to nine members of the recovery team.
17 May-21 May 77	A software modification was installed in one of the spacecraft's computers allowing its attitude control system to function without the pitch and yaw gyros. This action prevented loss of the spacecraft due to deterioration of the gyros and insured that the recovery of the spacecraft would be permanent.

LOSS AND RECOVERY OF THE FIRST DMSP BLOCK 5D SPACECRAFT, SEPTEMBER 1976 TO MAY 1977

A significant milestone in space technology was achieved on 24 March 1977 when a tumbling Air Force Weather satellite was successfully stabilized and put back into operation. The recovery of this satellite was precedent-setting because it was the first time that a spacecraft had been brough back to life after having been totally dead, with no power and no communication with earth. The Space and Missile Systems Organization (SAMSO), and especially its Defense Meteorological Satellite Program Office, played a leading role in the five-month effort leading to this remarkable achievement.

The satellite in question formed part of the Defense Meteorological Satellite Program (DMSP) system. The mission of the DMSP system was to provide weather information to the Department of Defense. The system consisted of a space segment, which gathered the information; a ground segment, which received and processed the information; and a communication segment, which transmitted the information from one ground station to another. The data thus obtained enabled forecasters to detect and observe developing weather systems, to track those systems even over remote areas such as oceans, and to provide battlefield commanders with reports on cloud cover, thunderstorms, and other weather phenomena which might affect military operations.[1]

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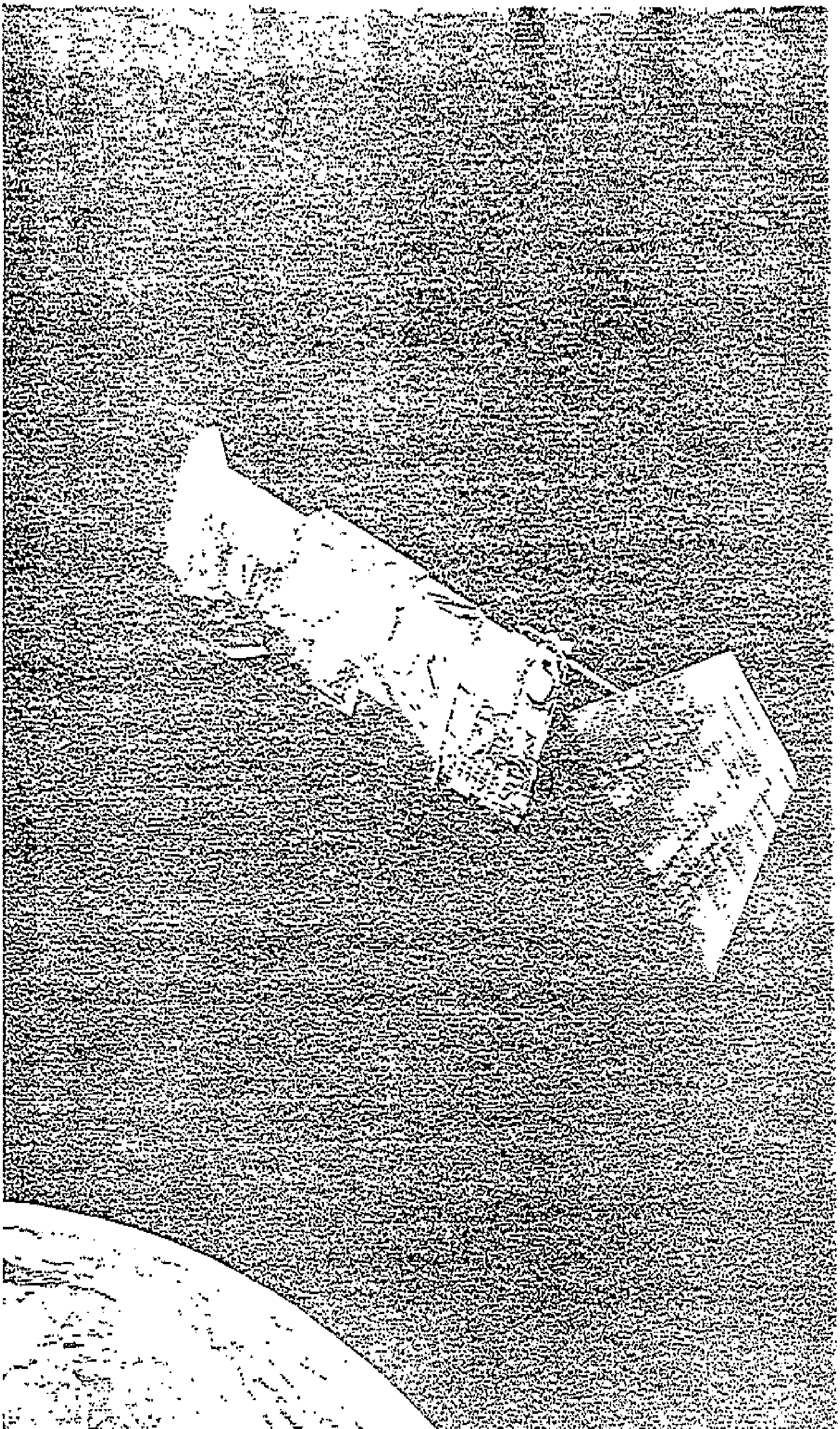
1. Fact Sheet (U), SAMSO/OI, "Defense Meteorological Satellite Systems Program," Apr 77.

Under normal circumstances, the space segment of the system was made up of a minimum of two satellites, both of which were in polar, sun-synchronous orbits. The satellites in orbit prior to 11 September 1976 were so-called Block 5C satellites, but the satellite launched on that date--the satellite that is the subject of this monograph--was the first of a new generation of satellites called the Block 5D. (See photograph) This satellite was four feet wide and 19.3 feet long with the solar array deployed, and it weighed approximately 1,055 pounds in orbit. A number of redundant components were incorporated into the 5D satellite, which increased its expected lifetime in orbit from 9 to 18 months. The satellite carried a primary sensor, the Operational Linescan System (OLS), which took images of cloud cover over the earth's surface during both day and night. In contrast to the primary sensor on the 5C, the OLS was able to provide images with nearly constant resolution across its entire scan path, which was 1600 nautical miles wide. In addition to this primary sensor, the satellite carried three special sensors: a gamma detector, which measured gamma radiation; a precipitating electron spectrometer, which allowed forecasters to determine the location and intensity of aurora; and a temperature/moisture sounder, which allowed forecasters to measure temperatures and concentrations of water vapor at different altitudes. While the first two special sensors were already being flown aboard Block 5C satellites, the third sensor was new. As the above description indicates, Block 5D satellites were to provide better performance and, hopefully, longer liftimes than



the Block 5C satellites previously in use, and for this reason special importance was attached to the launch of the first 5D vehicle.[2]

Preparations for launching the vehicle began on 29 June 1976, when the spacecraft was shipped to Vandenberg AFB. Testing at Vandenberg was complejted on 2 September, and launch occurred on 11 September. Launch, ascent, and injection into orbit all proceeded normally, but immediately after attaining orbit, the spacecraft became unstable and began to tumble. Because of the tumbling, the solar array was unable to track the sun, and the spacecraft lost power. Loss of power caused the transmitters aboard the spacecraft to cease functioning, and commuication between the spacecraft and the ground ceased. As a result of these de*velopments, the Air Force lost the services of a satellite that had cost $19.5 million to develop, build and launch.[3]

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2. Fact Sheet (U), SAMSO/OI, "Defense Meteorological Satellite Systems Program," Apr 77; "Block 5D Compilation" (U), SAMSO/YD, Jan 75.

3. Press Release (U), SAMSO/OI, "Air Force-Industry Team Revives $19.5 Million Weather Satellite," 4 Apr 77; Msg (U), SAMSO/XOP to CSAF et al, subj: "Meteorological Satellite On-Orbit Failure," 141910Z Sep 76 (Doc 1); Brfg (C), Col Ernest Schultz (SAMSO/YD) to LtGen Thomas W. Morgan (SAMSO/CC), "Report on F-1 Launch and Early Orbit Operations," 21 Sept 76; Brfg (U), Capt Terry Piddington, SAMSO/YDO, and Mr. David Griep, Aerospace Corp., to Lt Gen Thomas W. Morgan, SAMSO/CC, "DMSP Recovery," 12 Apr 77 (Doc 2).

The first order of business was to analyze the failure and determine its exact cause. The investigation of the failure was carried out by an independent review team established at the request of the SAMSO Commander, LtGeneral Thomas W. Morgan. The chairman of the team was Colonel Oliver W. Fix, the head of SAMSO's Defense Dissemination System Program Office. The members of the team were drawn from various offices within SAMSO, as well as from the National Aeronautics and Space Administration, the Aerospace Corporation, Lincoln Laboratory, Draper Laboratory, the Air Force Rocket Propulsion Laboratory, and Headquarters, Air Force Systems Command. The team was assisted by appropriate DMSP contractors.[4]

The team convened on 20 September 1976 and began to collect data on the failure of the satellite. The data available consisted of telemetry obtained from the spacecraft immediately before the failure and estimates of the spacecraft's motion provided by tracking radars of the Air Force Aerospace Defense Command. With the aid of this data, Aerospace Corporation experts programmed a computer to produce a three dimensional moving image of

4. Report , Col Oliver W. Fix, "Report of Investigation on IRON 5721, Defense Meteorological Satellite Program," no date (exerpts reproduced as Doc 3).

the spacecraft on a TV screen. This image showed how the spacecraft was behaving on orbit and how its behavior varied over time. By studying the image, the review team was able to conclude that the tumbling of the spacecraft was caused by a force that was striking the back of the spacecraft's solar array.[5]

Once this conclusion had been reached, the next step was to determine the source of the force in question. The three most likely sources were outgassing or micro-chuffing of the spacecraft's solid rocket motor, leakage of liquid hydrazine from the spacecraft's reaction control system, and leakage of gaseous nitrogen, also from the reaction control system. It was found that the force produced by outgassing of the solid rocket motor would not have proceeded from the right direction to have caused the vehicle to behave as it did and that the force produced by leakage of liquid hydrazine would have been so strong that it would have imparted a much higher spin rate to the vehicle. The force produced by leakage of gaseous nitrogen, however, would have proceeded from the right direction, and if all the gaseous nitrogen had leaked out of the reaction control system, it would have given the spacecraft

5. Ibid.; Report (U), Aerospace Corp., "DMSP Recovery," no date (Doc 4).

a spin rate equal to the one observed. It therefore appeared that the tumbling of the spacecraft had been caused by a gaseous nitrogen leak--a conclusion which was later confirmed when the spacecraft came back to life and it was found that all gaseous nitrogen had in fact escaped from the reaction control system.[6]

The final step in the failure analysis was to find out how the gaseous nitrogen had managed to escape from the reaction control system. The review team examined the system and found that it contained many B-nut connectors. In these connectors, a nut tightens a collar over the flared end of a piece of tubing to form what is intended to be a leak-tight joint. It seemed likely that a faulty B-nut may have permitted the gaseous nitrogen to escape from the reaction control system. If this were true, then it was the failure of a nut costing a few cents that had put the $19.5 million satellite out of business.[7]

Even before the failure analysis was complete, developments were taking place which would make it possible to recover the spacecraft. Early in October, natural

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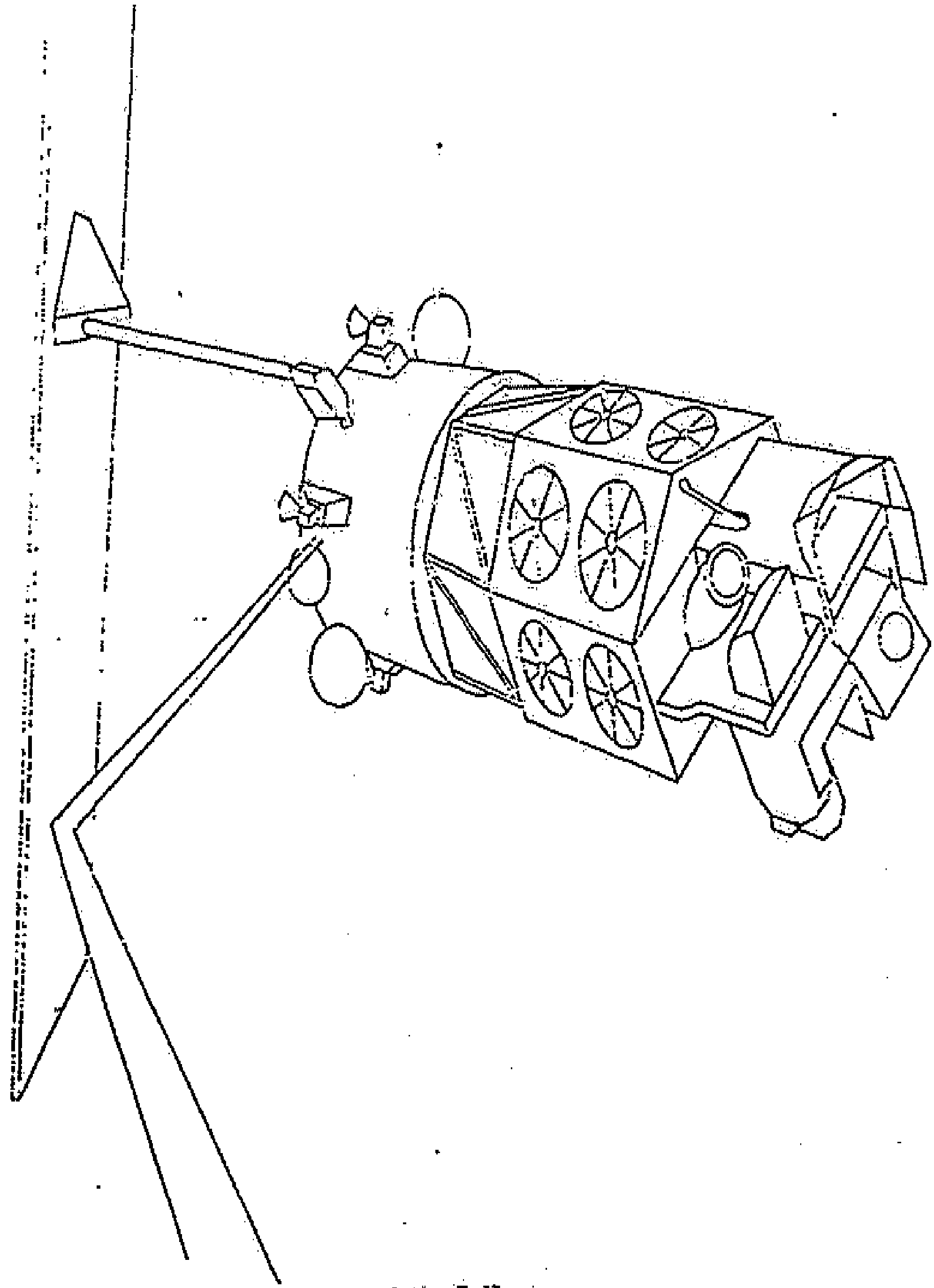
6. See note above.
7. See note 5.



Cause of the Failure:

Gaseous Nitrogen from the Attitude Control System Strikes the Solar Array of the Satellite

environmental forces caused the vehicle's spin vector to precess toward the sun. As a result, the spacecraft's solar array was again illuminated by sunlight, the solar panels began to generate power, and the communication system of the spacecraft came back to life. Personnel on the ground had anticipated these developments, and DMSP ground stations had therefore been making daily attempts to reestablish contact with the spacecraft. Contact was successfully reestablished on 5 October.[8]

Between 6 and 31 October, commands were sent to the spacecraft to stabilize the orientation of the spin axis and maximize the amount of solar illumination received by the solar array. In addition, all non-essential electrical loads aboard the spacecraft were turned off, and the spacecraft's battery was placed on maximum charge. These actions safeguarded the spacecraft's power supply and insured that communication between the spacecraft and the ground could continue. At the same time, all subsystems aboard the satellite were evaluated, to the extent that the spacecraft's motion would allow, and they all seemed to be performing normally. As a result, the DMSP Program Director decided that the satellite was worth the resources

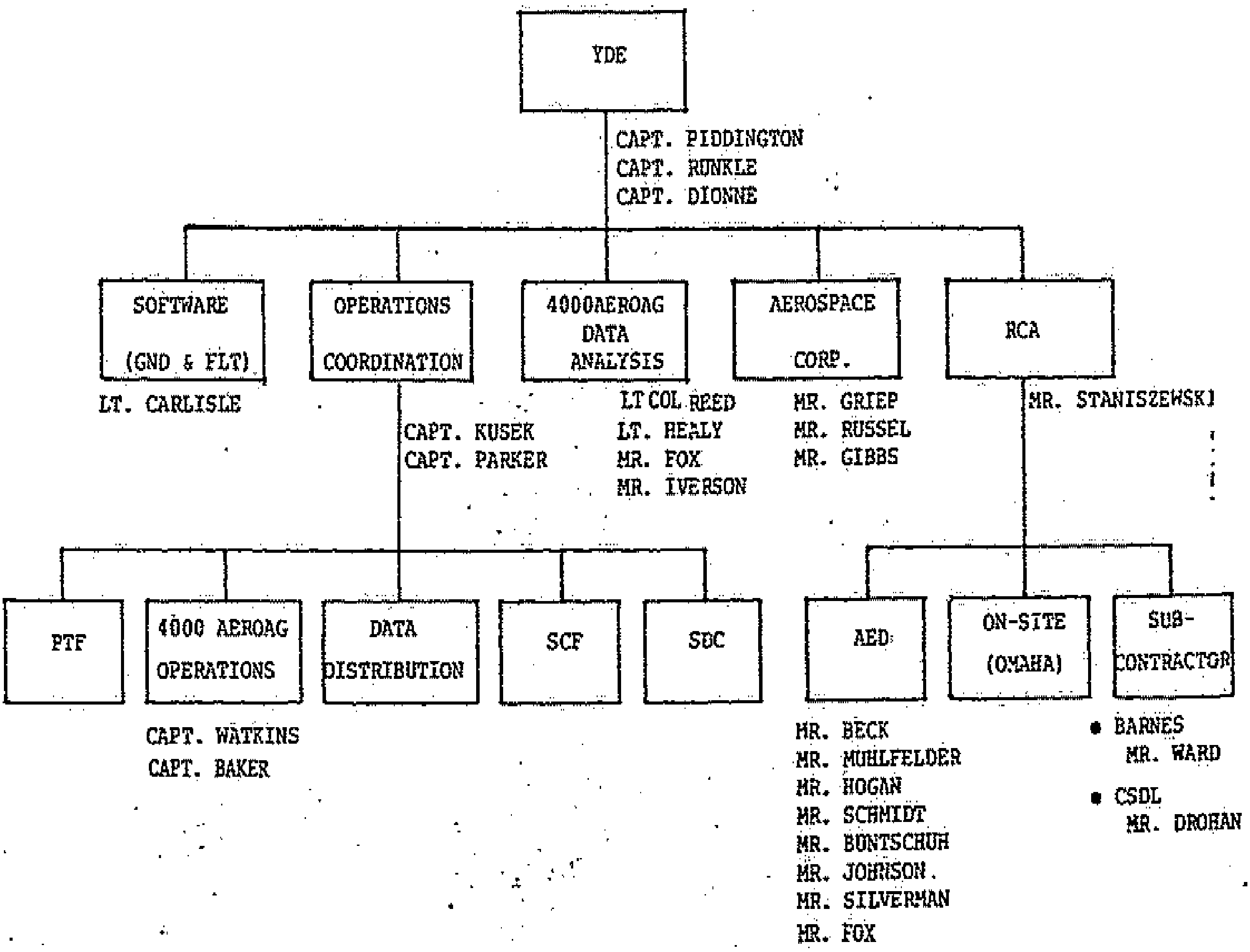
8. Hist Rpt (U), SAMSO/YDQ, 1 Jul-31 Dec 76; Comments made on original draft of this manuscript by SAMSO/YD.

that would have to be expended to save it, and efforts to recover the satellite were therefore initiated.[9]

Formulation of a recovery plan began on 1 November 1976, when a recovery team was organized. The team was made up of personnel from a number of organizations, including RCA, the Aerospace Corporation, the 4000th Aerospace Applications Group (4000 AEROAG), and the DMSP Program Office. The Program Office, which had supervised the design and fabrication of the satellite, was responsible for generating the recovery plan and managing the recovery attempt. RCA, the contractor that had built the satellite, was responsible for devising recovery procedures and for generating and integrating the software that would be needed during the recovery. The Aerospace Corporation, a Federal Contract Research Center that provided technical assistance to SAMSO, was responsible for validating the recovery plan and for investigating the effects of planned recovery actions on the satellite. Finally, the 4000 AEROAG, which exercised command and control over the satellite from its Command and Control Center at Offutt AFB, Nebraska, was responsible for

9. See note above; also see Brfg (S), AFSCF/DVR, "Defense Meteorological Satellite Program (DMSP)," 12 Jan 77 (Doc 5).

F-1 RECOVERY TEAM ORGANIZATION



implementing the recovery plan and making the actual recovery attempt.[10]

The objectives of the recovery were to restore the satellite to operating condition so that it could carry out its mission and to validate the Block 5D design in orbit prior to the launch of the next 5D vehicle. To accomplish these objectives, it would be necessary to reduce the satellite's rate of spin from 3.2 revolutions per minute to .03 revolutions per minute, at which point the spacecraft's attitude control system could take over and keep it stable. While carrying out this operation, two dangers had to be avoided. First, care had to be taken that sensitive hardware aboard the spacecraft did not receive too much exposure to the sun and become overheated. Second, equal care had to be taken that the spacecraft's solar array did not become oriented away from the sun. If this happened, the spacecraft would again lose power, communication between the spacecraft and the ground would cease, and recovery of the spacecraft might become impossible.[11]

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10. "DMSP F-1 Recovery Plan" (U), SAMSO/YD, 17 Nov 76; "Block 5D Compilation" (U), SAMSO/YD, Jan 75; Intvw (U), T.C. Hanley, Historian, with Capt Terry Piddington, SAMSO/YDO, 9 May 77.

11. "DMSP F-1 Recovery Plan" (U), SAMSO/YD, 17 Nov 76; Intvw (U), T.C. Hanley, Historian, with Mr. David Griep, Aerospace Corp., 26 Apr 77; Rpt (U), Aerospace Corp., "DMSP Recovery," no date (Doc 4).

In order to slow down the spacecraft's rate of spin, the recovery team decided to use the magnetic coils that formed part of the spacecraft's attitude control system. The attitude control system of the spacecraft was designed to counteract certain natural forces that tended to destabilize the spacecraft and throw it out of alignment.[12] It was made up of four gyroscopes, three sensors (an earth sensor, a sun sensor, and a star sensor), four reaction wheels, and two magnetic coils. (See illustration.) The gyroscopes and sensors measured changes in the spacecraft's attitude and channeled the data to the spacecraft's computer. When this data indicated that the spacecraft was out of alignment, the computer issued commands to the reaction wheels. The wheels then began to spin, and by so doing they were able to absorb the momentum that was throwing the spacecraft out of alignment. However, the more momentum the wheels had to absorb, the faster they had to spin, and if the momentum were not unloaded, they would eventually reach their limit. The

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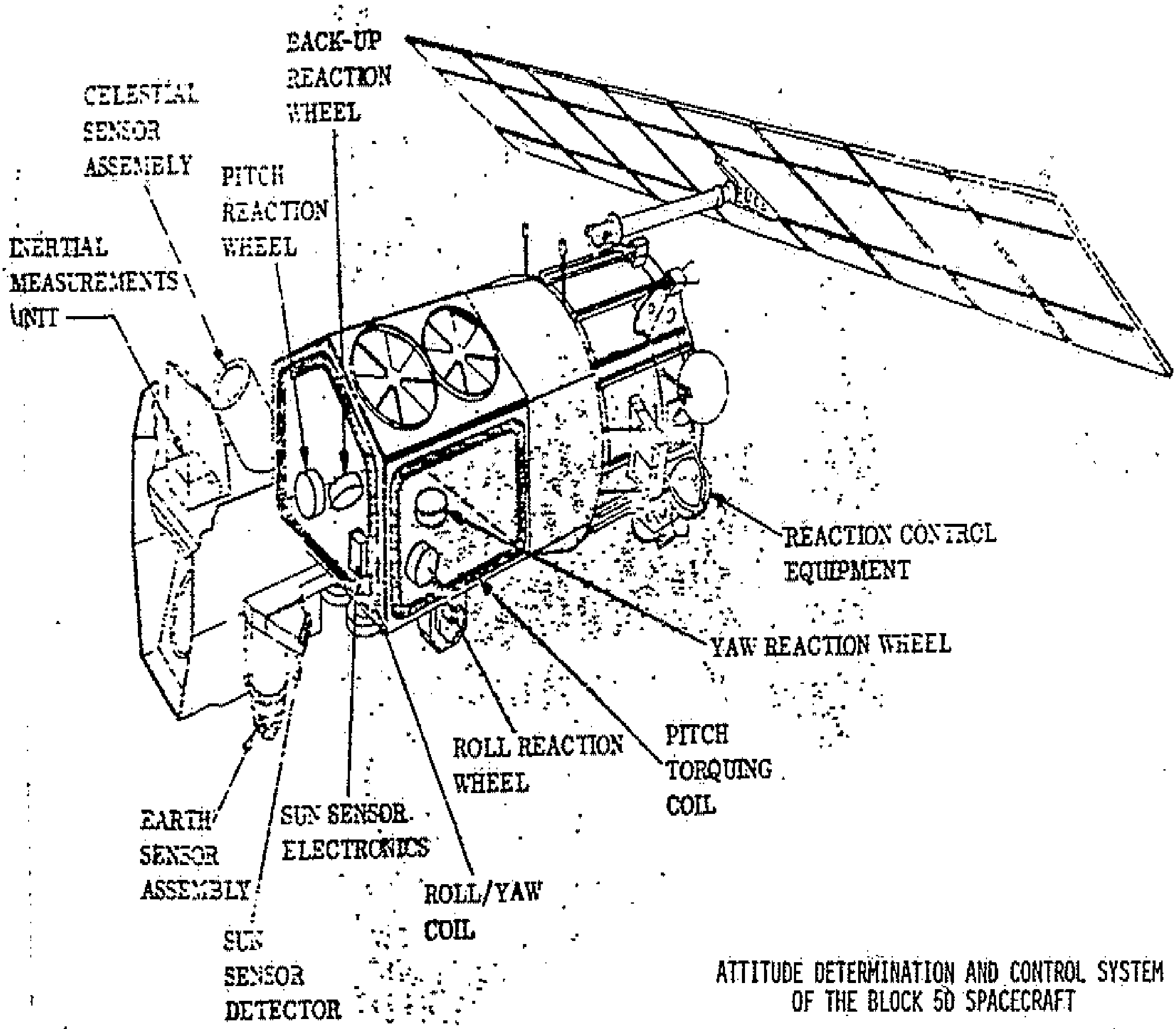
12. There were three such natural forces or phenomena that tended to destabilize the spacecraft: (1) interaction between the earth's magnetic field and the magnetic field set up about the spacecraft by electrical currents running through it, (2) variation in the earth's gravitational field caused by the fact that the earth is not perfectly round, and (3) pressure produced by solar radiation or particles. The first two forces were the primary ones affecting the DMSP satellite; the third was of lesser importance. (Intvw (U), T.C. Hanley, Historian, with Capt Terry Piddington, SAMSO/YDO, 27 Apr 77).



ATTITUDE DETERMINATION AND CONTROL SYSTEM
OF THE BLOCK 5D SPACECRAFT

wheels therefore had to be slowed down and the momentum removed from them.[13]

The wheels were slowed down and momentum was removed with the aid of the magnetic coils. When an electric current was passed through the coils, a magnetic field was set up about them, and the interaction of this magnetic field with the magnetic field of the earth imparted a torque--i.e., a twisting motion--to the spacecraft. As the reaction wheels were slowed down and released their momentum in one direction, the coils were used to generate a torque acting in the opposite direction. This torque cancelled out the momentum released by the wheels and allowed the wheels to be slowed down without destabilizing the spacecraft in the process.[14] Just as the coils could generate a torque that would counteract the momentum released by the reaction wheels, they could also generate a torque that would counteract the momentum of the spinning spacecraft. As a result, they could slow down the spinning and eventually stop it altogether.[15]

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13. Ibid.; Intvw (U), T.C. Hanley, Historian, with Mr. David Griep, Aerospace Corp., 26 Apr 77.

14. See note above.

15. Intvw (U), T.C. Hanley, Historian, with Mr. David Griep, Aerospace Corp., 26 Apr 77.

Once the decision had been made to despin the spacecraft by running electric current through the magnetic coils, a way had to be found to reverse the flow of current at periodic intervals during the despin process. The magnetic coils in the spacecraft would function like the coils in an electric motor. As current was fed into the coils, torque would be generated, but as the spacecraft rotated on its spin axis, the torque would reverse direction twice in every rotation. To prevent the torque from reversing direction in this manner, it was necessary to reverse the direction of the current instead, and the reversal had to be timed so that it would take place at the correct points in every rotation.[16]

The problem of how to time the reversal of current was solved by utilizing the spacecraft's earth sensor. The earth sensor consisted of four infrared-sensitive detectors that looked down at the earth from four sides of a pyramidal mounting. Under normal conditions, these detectors bracketed the earth within their fields of view, but with the spacecraft spinning, the earth was continually moving in and out of the field of view of each detector. Barnes Engineering Co., the manufacturer of the sensor, devised a scheme to take advantage of this situation and

16. Rpt (U), Aerospace Corp., "DMSP Recovery," no date (Doc 4).

use the sensor as a tachometer. Each time the earth entered the field of view of one of the detectors, a signal would be produced. These signals would indicate how fast the spacecraft was spinning and where it was in its rotation, and they could therefore be used to time the reversal of current in the magnetic coils.[17]

The reversal of current in the coils--and the operation of the coils in general--was to be controlled by computer. In the early stages of the recovery, both ground and flight computers were to be used. The ground computer would generate a set of tables that would indicate what factors should be taken into account in turning the magnetic coils on and off and in reversing the current in them. These tables would be radioed to one of the computers on board the spacecraft, and this computer, relying on the tables and on data from the earth sensor, would regulate the operation of the magnetic coils. Software that would allow the ground and flight computers to carry out these functions was developed by RCA, the spacecraft contractor, and by Barnes Engineering and Charles Stark Draper Laboratory, two of RCA's subcontractors.[18]

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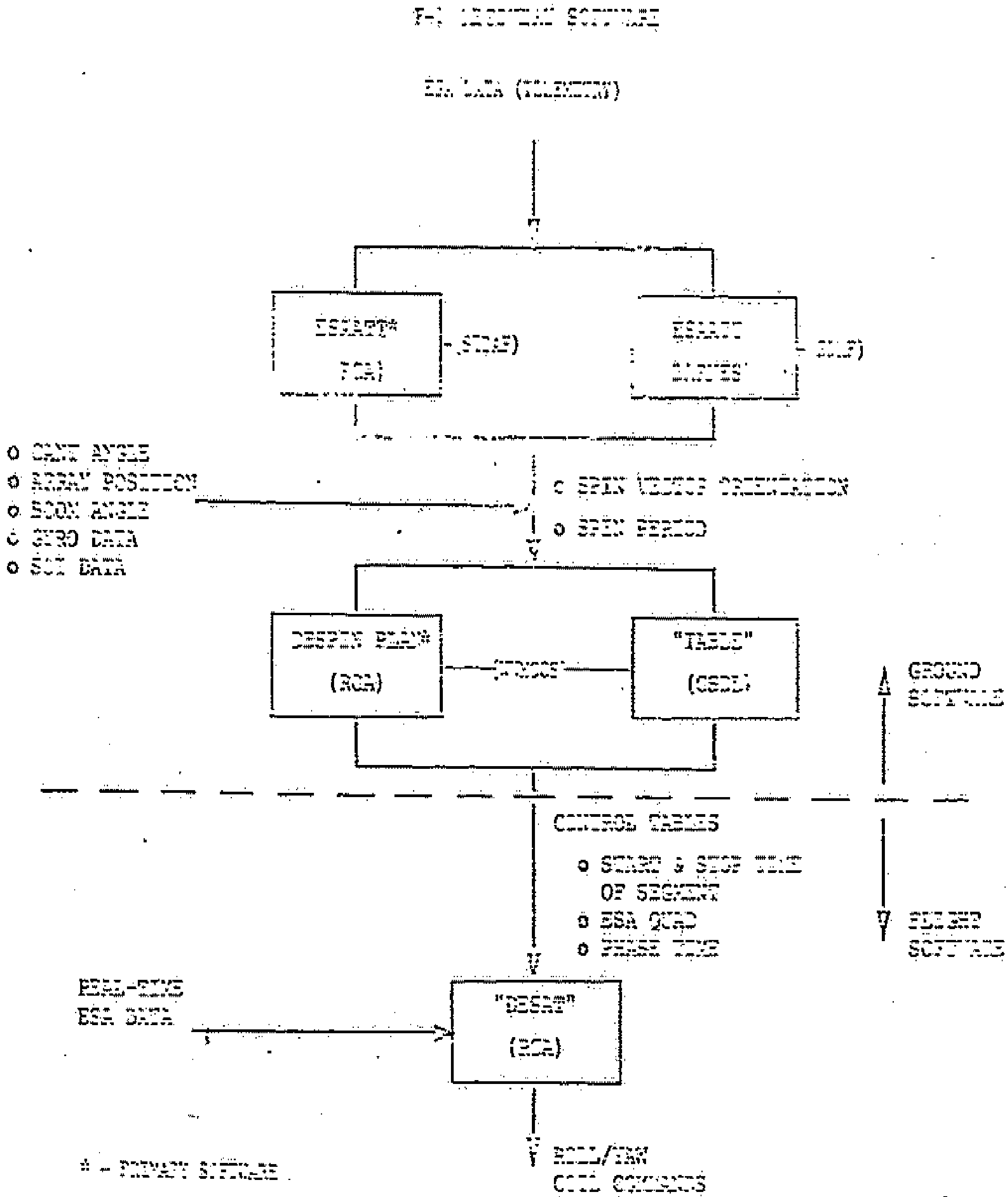
17. Ibid.
18. "DMSP F-1 Recovery Plan" (U), SAMSO/YD, 17 Nov 76; Intvw (U), T.C. Hanley, Historian, with Mr. David Griep, Aerospace Corp., 26 Apr 77.


ESA DATA
ESSAPT*
(STAF)
o CANT ANGLE
o ARRAY POSITION
o BOOM ANGLE
o GYRO DATA
o SPIN PERIOD
DESPIN PLAN*
(RCA)
"TABLE"
GROUND
CONTROL TABLES
OF SEGMENT
o ESA QUAD
REAL-TIME
ESA DATA
"DESAT"
(RCA)
ROLL/YAW

In addition to despinning the spacecraft, it was necessary to control the attitude of the spacecraft during the despinning process. The spacecraft's attitude was capable of being affected during that process by several environmental forces. The most important of these were gravity torques, generated by variations in the earth's gravitational field, and magnetic torques, arising from interaction between the earth's magnetic field and the residual magnetism of the spacecraft. Both of these forces were capable of shifting the orientation of the spacecraft's spin axis in a motion called precession. Unless controlled, precession might cause the spacecraft's solar array to move away from the sun, which would, in turn, cause the spacecraft to lose power and might make recovery impossible.[19]

Fortunately, precession could be controlled by the same method used to despin the spacecraft--that is, by passing electrical current through the magnetic coils. During the early phases of recovery, the pitch axis coil was to be used for precession control, and the current running through it was to be reversed every quarter orbit.

19. Rpt (U), Aerospace Corp., "DMSP Recovery," no date (Doc 4); Intvw (U), T.C. Hanley, Historian, with Capt Terry Piddington, SAMSO/YDO, 27 Apr 77.

This process, referred to as quarter orbit torquing, was to be initiated by commands from the ground, and, once initiated, was to be regulated by one of the spacecraft's on-board computers.[20]

In developing techniques for despinning the spacecraft and for controlling precession, the recovery team made extensive use of computer simulations. These simulations were computer programs incorporating mathematical models of the spacecraft and the space environment, and they were called simulations because they could be used to simulate the behavior of the spacecraft in orbit. Two simulations developed by the Aerospace Corporation were used in preparing for the early phases of recovery. The first of the two modeled the spacecraft as a single rigid body. It was initially used to study the environmental forces that would act on the spacecraft during recovery and was later used to develop and check out techniques for despinning the spacecraft and for controlling precession. The second simulation modeled the spacecraft as an articulated body composed of three segments--the spacecraft itself, the solar array boom, and the solar array. The solar array boom had failed to latch following deployment

20. "DMSP F-1 Recovery Plan" (U), SAMSO/YD, 17 Nov 76; Rpt (U), Aerospace Corp., "DMSP Recovery," no date (Doc 4).

of the array, and this second simulation was developed to study the effect that the unlatched boom would have on the motion of the spacecraft during despin. Both these simulations were fast-running; that is, they could be used to take the model spacecraft through a series of hypothetical on-orbit maneuvers at a speed hundreds of times faster than the speed at which the real spacecraft would go through the same maneuvers. As a result, it was possible for the recovery team to determine, in a relatively short period of time, how the spacecraft would respond to a given recovery procedure over the course of many orbits.[21]

Once techniques had been developed for despinning the spacecraft and controlling precession, the way was clear for the start of the recovery. The recovery was carried out by the 4000 AEROAG, a unit of the Strategic Air Command. The 4000 AEROAG installed and tested the computer programs to be used during recovery, it commanded the spacecraft during despin operations, and it received telemetry from it during those same operations. This telemetry provided data on the health and status of the

21. Rpt (U), Aerospace Corp., "DMSP Recovery," no date (Doc 4); Rpt (U), Aerospace Corp., "Aerospace DMSP F-1 Recovery Simulation Results," 17 Dec 76; Paper (U), D.J. Griep, Aerospace Corp., "Aerospace DMSP Recovery Activities," 6 Dec 76.

spacecraft--especially on the condition of its power subsystem, the temperature of spacecraft components, and the attitude and spin rate of the spacecraft. The 4000 AEROAG conducted the recovery from its Command and Control Center at Offutt AFB, Nebraska, and used its Command Readout Stations at Fairchild AFB, Washington, and Loring AFB, Maine, to relay commands to the satellite and receive telemetry from it.[22]

The 4000 AEROAG was assisted in the recovery operation by SAMSO's Satellite Control Facility and by the Space Object Identification Division of the Aerospace Defense Command. The Satellite Control Facility made its ground stations available to the 4000 AEROAG to assist the Command Readout Stations in relaying commands to the satellite and receiving telemetry from it. The Space Object Identification Division used its narrow band radars at various sites around the world to collect data on the attitude of the spacecraft during recovery. This data was supplemented by data gathered by Lincoln Laboratory's wide-band radar located at Kwajalein Island in the Pacific.[23]

22. "DMSP F-1 Recovery Plan" (U), SAMSO/YD, 17 Nov 76; "Block 5D Compilation" (U), SAMSO/YD, Jan 75.

23. Intvw (U), T.C. Hanley, Historian, with Capt J.C. Ray, AFSCF/DVR, 10 May 77; "DMSP F-1 Recovery Plan" (U), SAMSO/YD, 17 Nov 76; Capt Emery Wilson and Sgt Jim Schultz, "'500-Mile Screwdriver' Saves DMSP Satellite," Astronews, 29 Apr 77.

The recovery of the satellite was carried out in three phases. During Phase I, which lasted from 30 November to 3 December 1976, recovery procedures were tested and their workability was demonstrated. In the process, the spin rate of the spacecraft was reduced from 3.2 revolutions per minute to 2.8 revolutions per minute. During Phase II, a more substantial reduction in the spin rate was achieved, with the rate being reduced from 2.8 to .5 revolutions per minute. This phase was carried out in two increments, which lasted from 16 January to 20 January and from 26 January to 30 January 1977 respectively. Completion of Phase II opened the way for Phase III, during which the spin rate would be reduced from .5 to .03 revolutions per minute, allowing the spacecraft's normal attitude control system to take over and stabilize the vehicle the rest of the way.[24]

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24. "DMSP F-1 Recovery Plan" (U), SAMSO/YD, 17 Nov 76; Rpt (U), Aerospace Corp., "DMSP Recovery," no date (Doc 4); Brfg (S), AFSCF/DVR, "Defense Meteorological Satellite Program (DMSP)," 12 Jan 77 (Doc 5); Rpt (U), 4000 AEROAG/ENY, "Report No. 291-Special Report-Despin Phase II, Increment 1, Evaluation," 25 Jan 77; Ltr (U), SAMSO/YDO to SAMSO/YD, subj: "Monthly Activity Reports-January/February 1977," 9 Mar 77; Intvw (U), T.C. Hanley, Historian, with Capt Terry Piddington, SAMSO/YDO, 9 May 77; Brfg (U), Col R.J. Fox, SAMSO/YD to LtGen T.W. Morgan, SAMSO/CC, "Defense Meteorological Satellite Program (DMSP)," 31 May 77.

Phase III was the most difficult phase of the recovery because of special problems that arose as the spacecraft's rate of spin was reduced to a low level. One of these problems had to do with the earth sensor assembly. As the spin rate was reduced, the earth sensor assembly gave fewer and fewer readings of the earth's horizon and became less and less useful as a source of data on the spacecraft's attitude or spin angle. RCA, the spacecraft contractor, first proposed getting around this problem by deriving spin angle data from the spacecraft's gyros rather than from the earth sensor. In order to do this, however, it would have been necessary to change the main computer program in the spacecraft. This would have been a major task, and if an error had been made in the course of it, it could have affected any of the computer functions carried out in the spacecraft. RCA, therefore, decided to continue to rely on the earth sensor assembly but to reorient the spin vector of the spacecraft so that the earth sensor would give as many readings of the horizon as possible. This was accomplished by changing the position of the solar array, which changed the spacecraft's center of gravity and thereby reoriented the spin vector.[25]

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25. Rpt (U), Aerospace Corp., "DMSP Recovery," no date (Doc 4); Intvw (U), T.C. Hanley, Historian, with Capt Terry Piddington, SAMSO/YDO, 9 May 77.

A second problem that arose as the spin rate was reduced involved the spacecraft's motion about its spin axis. The spacecraft behaved like a top. As long as it was spinning rapidly, it remained fairly stable, but as it began to spin more slowly, it became unstable and began to wobble. This wobbling, referred to as nutation, was enhanced by the torque that was being applied to the spacecraft to slow down the spin rate. Unfortunately, this torque was not ideally aligned for despinning the spacecraft, and it tended not only to slow down the spin rate but also to upset the spacecraft as it spun on its axis. The effect was not signicant as long as the spacecraft was spinning rapidly and remained relatively stable, but it became more pronounced as the spacecraft slowed down, began to wobble, and became more vulnerable to the influence of disturbing forces. Unless the wobbling or nutation of the spacecraft could be controlled, the spacecraft's solar array might be turned away from the sun, power might be lost, and communication between the spacecraft and the ground might become impossible.[26]

26. Intvw (U), T.C. Hanley, Historian, with Capt Terry Piddington, SAMSO/YDO, 27 Apr 77; Intvw (U), T.C. Hanley, Historian, with Mr. Ramunas J. Skrinska, Aerospace Corp., 6 Jun 77; Rpt (U), Aerospace Corp., "DMSP Recovery," no date (Doc 4).

To control nutation, two steps were taken. First, one of the spacecraft's reaction wheels was spun at a constant rate to stiffen the spacecraft's spin axis and give it more stability. Second, one of the gyros aboard the spacecraft was used to sense nutation, and another of the reaction wheels was spun at a varying rate to counteract it. The first procedure was known as momentum bias and the second as active nutation damping.[27]

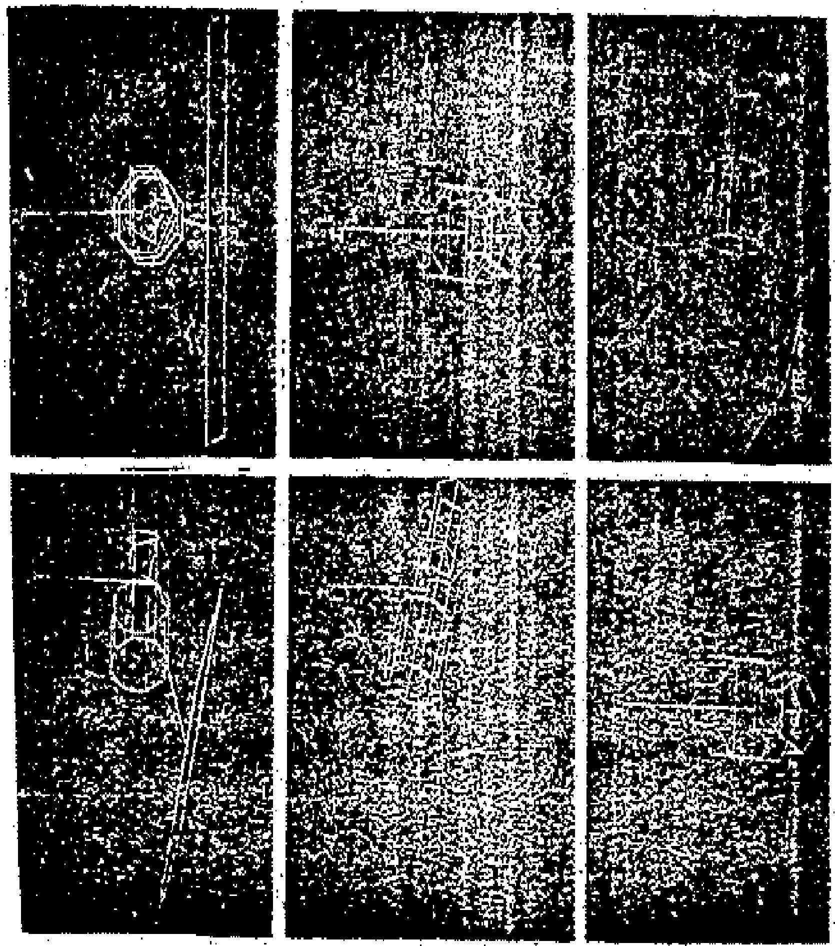
A third problem that arose in preparing for the final stage of recovery had to do with the difficulty of directing the recovery from the ground. This difficulty stemmed from two factors. First, long periods of time were required to process telemetry from the satellite and generate the commands that would govern the despinning process. Second, the ground stations that were used to send these commands to the satellite were spaced at relatively wide intervals around the globe, and the satellite was out of sight of these stations for extended periods. While it was out of sight, no commands could be sent to it. These factors were not a problem during the early phases of recovery, when despinning the spacecraft was a fairly straightforward process, but they became a problem during the third and

27. Brfg (U), Capt Terry Piddington, SAMSO/YDO, and Mr. David Griep, Aerospace Corp., to LtGen T. W. Morgan, SAMSO/CC, "DMSP Recovery," 12 Apr 77 (Doc 2); Intvws (U), T.C. Hanley, Historian, with Capt Terry Piddington, SAMSO/YDO, 27 Apr 77 and 9 May 77; Intvw (U), T.C. Hanley, Historian, with Mr. Ramunas J. Skrinska, Aerospace Corp., 6 Jun 77.

final phase, when the task of controlling the spacecraft's attitude became very demanding. For this reason, the entire job of despinning the spacecraft and controlling its attitude was turned over to the spacecraft's on-board computer, and all of the software required for these operations was uploaded into that computer. Hardware on the ground was used only to initiate major events during Phase III and to monitor these events while they were going on.[28]

In working out the recovery procedures to be used in Phase III, extensive use was made of a so-called hybrid interactive simulation developed by the Aerospace Corporation. This simulation was similar to the simulations developed by Aerospace for Phases I and II of the recovery, but it differed from them in one important respect. Whereas the other two simulations provided data only in the form of paper printouts, the hybrid interactive simulation provided both paper printouts and a three-dimensional moving representation of the spacecraft on a TV screen. By

28. Intvw (U), T.C. Hanley, Historian, with Mr. David Griep, Aerospace Corp., 26 Apr 77; Intvw (U), T.C. Hanley, Historian, with Capt Terry Piddington, SAMSO/YDO, 27 Apr 77; Memo for Record (U), Maj John C. Koger, SAMSO/YDE, subj: "Ground Support System for F-1 Recovery," 18 Nov 76; Rpt (U), Aerospace Corp., "DMSP Recovery," no date (Doc 4); Brfg (U), Capt Terry Piddington, SAMSO/YDO, and Mr. David Griep, Aerospace Corp., to LtGen T.W. Morgan, SAMSO/CC, "DMSP Recovery," 12 Apr 77 (Doc 2).



Images of the DMSP Spacecraft Generated by the Hybrid Interactive Simulation

watching this representation, a viewer could see how the spacecraft would respond to a variety of recovery procedures, implemented under a variety of conditions. Thus, the hybrid interactive simulation could be used to investigate various strategies for despinning and controlling the spacecraft and could assist in the development of the final recovery sequence.[29]

29. Rpt (U), Aerospace Corp., "DMSP Recovery," no date (Doc 4); Rpt (U), Aerospace Corp., "Aerospace DMSP F-1 Recovery Simulation Results," 17 Dec 76; Paper (U), D.J. Griep, Aerospace Corp., "Aerospace DMSP Recovery Activities," 6 Dec 76.

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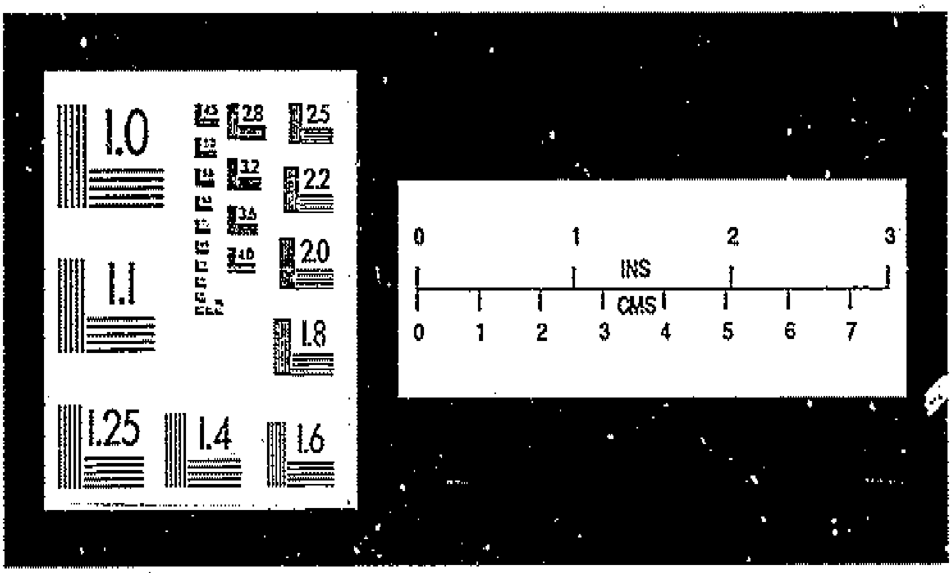

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The hybrid interactive simulation allowed the recovery team to predict, with a high degree of confidence, that the recovery procedures developed for Phase III would function successfully. There was still a chance that something might go wrong, however, and for this reason it was essential to monitor the status of the spacecraft during recovery operations. To help it do this, the recovery team had a new display terminal installed in the Command and Control Center at Offutt AFB. Telemetry from the spacecraft was received by the DMSP and Satellite Control Facility ground stations and was relayed to the Command and Control Center, where it was received, processed, and displayed on the new terminal. The terminal provided computer printouts, kinescope displays of selected telemetry tables, and strip chart recordings which allowed analysts to monitor the progress of recovery maneuvers, the status of the spacecraft's power subsystem, and the temperature of vital satellite components. If the data presented by the terminal indicated that something was going wrong during the recovery, the spacecraft would be spun up into a safe condition while the recovery team studied the problem and devised a solution.[30]

30. Memo for Record (U), Maj John C. Koger, SAMSO/YDE, subj: "Ground Support System for F-1 Recovery," 18 Nov 76; Ltr, (U), J.R. Staniszewski, RCA, to C.S. Constantino, RCA, subj: "Recovery and Early Orbit Operation of the Block 5D-1, F-1 Spacecraft-March 24 to April 1, 1977," 7 Apr 77 (Doc 6);

The initial attempt to execute Phase III of the recovery was carried out on 28 February 1977. At first everything went according to plan, but as the attempt progressed, an abnormality was detected in one of the spacecraft's gyros. The gyros formed part of the spacecraft's attitude determination and control system, which was to go into operation once recovery was complete. If the system were put into operation with one of the gyros in a sick condition, it might not be able to do its job properly, and the spacecraft might be lost again. The recovery attempt was therefore terminated and the spacecraft spun up and stabilized while the problem was studied.[31]

Analysis of the problem revealed that not just one but all three of the spacecraft's gyros were malfunctioning. It was determined that the gyros had been damaged, probably by exposure to extreme temperatures following the initial loss of the spacecraft, and that they were drifting at an abnormal rate. For the time being, it would be possible to continue using the gyros by making allowances for the

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30. Cont. Intvw (U), T.C. Hanley, Historian, with Capt Terry Piddington, SAMSO/YDO, 27 Apr 77.

31. Brfg (U), Capt Terry Piddington, SAMSO/YDO, and Mr. David Griep, Aerospace Corp., to LtGen T.W. Morgan, SAMSO/CC, "DMSP Recovery," 12 Apr 77 (Doc 2); Ltr (U), J.R. Staniszewski, RCA, to C.S. Constantino, RCA, subj: "Recovery and Early Orbit Operation of the Block 5D-1, F-1 Spacecraft-March 24 to April 1, 1977," 7 Apr 77 (Doc 6); Intvw (U), T.C. Hanley, Historian, with Capt Terry Piddington, SAMSO/YDO, 9 May 77.

drift, but as time went by, the gyros might deteriorate further and might eventually fail altogether. In response to this situation, it was decided to go ahead with the recovery, relying on the gyros as long as they were still usable to some extent, and at the same time to develop a software package that would allow the attitude control system to function without the gyros.[32]

Following this decision, recovery operations were resumed, and final recovery of the spacecraft was successfully completed on 24 March 1977. The spacecraft's computer was programmed to make allowances for gyro drift, and the spin rate of the spacecraft was reduced to .03 revolutions per minute. At this point, the spacecraft's attitude control system began normal operations, and the recovery was complete.[33]

Once recovery was accomplished, the next task was to finalize the software that would allow the attitude control system to function without the gyros. Unfortunately, one of the gyros--the roll gyro--had begun to deteriorate at an alarming rate and estimates indicated that it would fail

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32. Brfg (U), Capt Terry Piddington, SAMSO/YDO, and Mr. David Griep, Aerospace Corp., to LtGen T.W. Morgan, SAMSO/CC, "DMSP Recovery," 12 Apr 77 (Doc 2); Ltr (U), J.R. Staniszewski, RCA, to C.S. Constantino, RCA, subj: "Recovery and Early Orbit Operation of the Block 5D-1, F-1 Spacecraft-March 24 to April 1, 1977," 7 Apr 77 (Doc 6).

33. See note above.

on 29 March, well before the complete software package could be tested and installed. However, Draper Laboratory was able to devise an interim solution--a software "patch" that allowed the attitude control system to dispense with the roll gyro and derive the spacecraft's roll rate from the earth sensor. This modification was successfully installed in one of the spacecraft's computers on 28 March. Work then went ahead on a software modification that would allow the system to operate without the other two gyros as well. This second modification was successfully installed in the computer during the period 17 to 21 May, and the future survival of the spacecraft was thus insured.[34]

The recovery of the DMSP spacecraft was expensive, costing approximately $2 million, but it produced several important benefits. First, it returned the spacecraft to operational status and allowed it to carry out its mission--that of providing worldwide weather information to the Department of Defense. The spacecraft had been providing that information since 1 April 1977 when it had been officially declared operational by the Air Force. Second, the recovery permitted the performance of the Block 5D satellite to be evaluated on orbit before the launch of the next 5D vehicle. This evaluation showed that the

34. See note 31. Also, Brfg (U), Col R.J. Fox, SAMSO/YD, to LtGen T.W. Morgan, SAMSO/CC, "Defense Meteorological Satellite Program (DMSP)," 31 May 77.

satellite's primary sensor was more sensitive to transient radiation than had been anticipated, and the sensors to be used on future satellites were modified as a result. Third, the recovery experience allowed the DMSP's command and control system to be evaluated. Evaluation of this system indicated that a direct data circuit was needed to connect the Satellite Test Center at Sunnyvale with the Command and Control Center at Offutt, and such a circuit was in fact installed after the recovery was completed.[35]

Not only was the recovery of the DMSP spacecraft beneficial; it was also precedent-setting. It was the first recovery in which a spacecraft had been brought back to life after having been totally dead, with no power and no communication with earth, and the first in which a three-axis-stabilized vehicle had been successfully despun. It was also the first recovery in which on-board magnetic coils, controlled by specially developed computer programs, had been used to despin a vehicle. This approach, now that it had been developed, was available for use in recovering similar spacecraft that might suffer similar problems in the future.[36]

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35. Brfg (U), Capt Terry Piddington, SAMSO/YDO, and Mr. David Griep, Aerospace Corp., to LtGen T.W. Morgan, SAMSO/CC, "DMSP Recovery," 12 Apr 77 (Doc 2); Intvw (U), T.C. Hanley, Historian, with Capt J.C. Ray, AFSCF/DVR, 10 May 77; Capt Emery Wilson and Sgt Jim Schultz, "'500-Mile Screwdriver' Saves DMSP Satellite," Astronews, 29 Apr 77; Intvw (U), T.C. Hanley, Historian, with LtCol Stephen McElroy, SAMSO/YDO, 3 Aug 77.

36. Intvw (U), T.C. Hanley, Historian, with Mr. David

Several factors made the recovery possible, of which three in particular stand out. The first of these was the presence of reprogrammable computers on board the spacecraft. If these computers had not been present on the spacecraft, the recovery team could not have uploaded the computer programs necessary for despinning the spacecraft and for modifying the attitude control system so that it could operate without the gyros. The second factor was the availability of computer simulation techniques. Through the use of these techniques, it was possible to predict how the spacecraft would behave when the recovery plan was put into effect and to remove the bugs from the plan before it was implemented. The third factor permitting recovery of the spacecraft was the expertise, teamwork, and dedication exhibited by the recovery team itself. The members of the team, drawn from SAMSO, the 4000 AEROAG, the Aerospace Corporation, RCA, and other organizations within the Air Force and private industry, worked 12 hours a day, six days a week while the recovery was being planned, and 24 hours a day, seven days a week during those periods when the recovery was actually being executed. All told, the effort expended in recovering the DMSP spacecraft

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36. Cont. Griep, Aerospace Corp., 26 Apr 77; Intvw (U), T.C. Hanley, Historian, with Capt Terry Piddington, SAMSO/YDO, 27 Apr 77.

was equivalent to the effort that would normally be expended in developing the software for the attitude control system of an entirely new satellite.[37]

The achievements of the recovery team were given prompt and full recognition by Air Force officials. Mr. Jack Martin, Acting Secretary of the Air Force, General David C. Jones, Air Force Chief of Staff, and General William Evans, Commander of AFSC, all congratulated the members of the team on their achievements. In addition, General Evans presented awards to nine members of the team during his visit to SAMSO on 28 April 1977. Meritorious Service Medals were given to Captain Terry Piddington, who had directed the recovery team, and to LtColonel Stephen McElroy, Captain Robert Kusek, and Captain Robert S. Parker. Five other officers received Air Force Commendation Medals: Captain Eugene Dionne, Captain Marty Runkle, First Lieutenant Robert Carlisle, First Lieutenant Donald Healy, and Captain Dale Conrad.

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37. See note above. Also, Brfg (U), Capt Terry Piddington, SAMSO/YDO, and Mr. David Griep, Aerospace Corp., to LtGen T.W. Morgan, SAMSO/CC, "DMSP Recovery," 12 Apr 77 (Doc 2); Ltr (U), J.R. Staniszewski, RCA, to C.S. Constantino, RCA, subj: "Recovery and Early Orbit Operation of the Block 5D-1, F-1 Spacecraft-March 24 to April 1, 1977," 7 Apr 77 (Doc 6).

Eight of the officers receiving medals were assigned to SAMSO's DMSP Program Office, while one--Captain Conrad--was assigned to the Air Force Satellite Control Facility.[38]

38. Ltr (U), Mr. Jack Martin, Acting Secretary of the Air Force, to LtGen T.W. Morgan, SAMSO/CC, 31 Mar 77 (Doc 7); Ltr (U), Gen D.C. Jones, USAF/CC, to Gen W.J. Evans, AFSC/CC, subj: "Letter of Appreciation," 7 Apr 77 (Doc 8); Msg (U), Gen W.J. Evans, AFSC/CC, to LtGen T.W. Morgan, SAMSO/CC, subj: "Defense Meteorological Satellite Program (DMSP) Flight 1 Recovery," 291540Z Mar 77 (Doc 9); Ltr (U), LtGen T.W. Morgan, SAMSO/CC, to AFSC/DP, subj: "Recommendation for Award to the DMSP F-1 Recovery Team," 13 Apr 77, with 5 atchs (Doc 10); Intvw (U), T.C. Hanley, Historian, with MSgt H.A. Lofton, SAMSO/YDX, 10 May 77; Intvw (U), T.C. Hanley, Historian, with Capt Sally Davidson, SAMSO/CSP, 9 Jun 77.

APPENDIX:

MEMBERS OF THE DMSP RECOVERY TEAM

I. Members from the DMSP Program Office (SAMSO/YD)

Capt Terry Piddington
Capt Robert M. Kusek
Capt Robert S. Parker
Capt Eugene R. Dionne
Capt Marty T. Runkle
1Lt Robert J. Carlisle, III
1Lt Donald J. Healy, Jr.

II. Members from the Air Force Satellite Control Facility

Capt Dale D. Conrad

III. Members from the 4000th Aerospace Applications Group (4000 AEROAG)

LtCol William Reed
Capt Dean Baker
Capt Warren Watkins
Capt Steve Stadler

IV. Members from the Space Defense Center of the Aerospace Defense Command

Capt Chris Henley

V. Members from the Aerospace Corporation

David J. Griep
Ramunas Skrinska
Jesse Lopez
William Russell
Morey Gibbs
William L. Hayden

VI. Members from RCA

Dr. W. Manger
J.R. Staniszewski
G. Beck
L. Muhlfelder
R. Hogan
R. Buntschuh
M. Silverman
C. Fox
D. Iverson

VII. Members from Barnes Engineering Company

Ken Ward

VIII. Members from the Charles Stark Draper Laboratory

W. Drohan
B. Dinak

IX. Members from Hughes Corporation

Jerry Adams
Jerry Salvatoria

GLOSSARY

AED	Astro-Electronics Division of RCA
AFB	Air Force Base
AFSC	Air Force Systems Command
Attitude control system	System that controlled the attitude of the DMSP spacecraft once it attained orbit so as to permit precise pointing of the primary sensor
Chuffing	An intermittent decline and pickup in the combustion process of a rocket engine
Command	To send a signal or series of signals to a spacecraft to cause it to start, stop, or continue some operation
CSDL	Charles Stark Draper Laboratory
Despin	To reduce the spin rate of a spacecraft; cause it to spin more slowly
DMSP	Defense Meteorological Satellite Program
Drift	Change in the spin rate of a gyro caused by aging or malfunctioning of the instrument
ESA	Earth Sensor Assembly
ESAATT	ESA Attitude Determination ground support computer program
4000 AEROAG	4000th Aerospace Applications Group
Kinescope	A cathode ray tube designed for reproducing television images
OLS	Operational Linescan System
Nutation	Wobbling of a spacecraft about its axis of rotation; similar to the nodding of a top
Pitch axis	Short horizontal axis of a spacecraft
Polar orbit	An orbit that passes over or near the earth's poles
Precession	A constant movement of a spacecraft's axis of rotation due to the influence of natural forces

PTF	Payload Test Facility
RCA	Radio Corporation of America
Reaction control system	System used to control the attitude of the DMSP spacecraft during its ascent into orbit
Recovery	Restoration of an orbiting satellite to operational condition
Roll Axis	Long horizontal axis of a spacecraft
SAMSO	Space and Missile Systems Organization
SCF	Satellite Control Facility
SDC	Space Defense Center (Aerospace Defense Command)
SDMF	Software Development and Maintenance Facility
Sensor	A device that seeks out or detects a particular stimulus--as from heat, light, sound, or motion--and then reacts in ways determined by the function of the device
SIDAF	Stored Telemetry Interactive Data Analysis Facility
Spin vector	Vector along a spacecraft's axis of rotation
Simulation	Representation of physical objects and phenomena by a computer
Software	Procedures, instructions, data, etc., required for operation of a computer
SOI	Space Object Identification
Solar array	Device aboard a satellite that converts sunlight into electrical energy
Spin up	To increase the spin rate of a spacecraft; cause it to spin faster
Sun-synchronous orbit	Orbit which permits a satellite to face the sun at all times
Tachometer	A speed counter; device that measures revolutions per minute of an engine
Telemetry	Data transmitted from a satellite to a ground station by radio signal
Three-axis stabilized	Said of a satellite that is stabilized along all three axes--pitch, roll, and yaw
Torque	A force which produces or tends to produce rotation
Transient radiation	Particles such as protons, neutrons, and helium molecules emitted by the sun and other stellar sources

WWMCCS	World Wide Military Command and Control Systems
Yaw axis	Vertical axis of a spacecraft
YDE	Directorate of Engineering in SAMSO's DMSP Program Office